Wireless Netw
DOI 10.1007/s11276-009-0166-1

Route duration modeling for mobile ad-hoc networks

**Michael Pascoe-Chalke · Javier Gomez ·
Victor Rangel · Miguel Lopez-Guerrero**

Abstract In this paper, we present a model that estimates the time duration of routes formed by several intermediate nodes in mobile multi-hop ad-hoc networks. First, we analyze a 3-node route, where only the intermediate node is in movement while source and destination nodes remain static. From this case, we show how route duration is affected by the initial position of the intermediate node and the size of the region where it is located. We also consider a second case where all nodes of 3-node routes are mobile. Based on extensive analysis of these routes, we determine the PDF of route duration under two different mobility models. This PDF can be determined by either analytical or statistical methods. The main contribution of this paper is that the time duration of a route formed by *N* intermediate nodes can be accurately computed by considering the minimum route duration of a set of *N* routes of 3 nodes each. Simulation work was conducted using the NS-2 network simulator to verify the accuracy of the proposed model and to compare it with other proposals found in the literature. We show that our model is in better agreement with simulation results as compared with other models. Results from this work can be used to compute overhead signaling during route-maintenance of unicast and multicast routing protocols for mobile ad-hoc networks. Similarly, because route duration decreases with route length, this study can be used to scale the network size up/down.

Keywords Ad-hoc networks · Route duration · MANET

1 Introduction

An ad-hoc network is a collection of nodes forming a temporary network by means of wireless interfaces and without use of any existing network infrastructure or centralized administration. Different types of ad-hoc networks are becoming increasingly popular: Vehicular Ad-hoc Networks (VANETs), Wireless Sensor Networks (WSNs) and Mobile Ad-hoc Networks (MANETs). In MANETs, the nodes self-organize and are free to move randomly. The network topology may thus change rapidly and unpredictably. Such a network may operate in a standalone fashion, or may be connected to the Internet. MANETs became a popular subject for research as laptops and 802.11/Wi-Fi wireless networks were widespread in the late 1990s. Degree of mobility is an important factor and a key research issue in MANET and VANET networks. Although, at this moment, most sensor applications have zero or low mobility, it can be anticipated that future sensor network applications would also involve some degree of mobility [5].

Due to the limited transmission range of wireless radio transceivers, there may be a need for one or multiple nodes (intermediate forwarding nodes) working as relays (multi-hop routing) between source-destination pairs in an

M. Pascoe-Chalke (✉) · J. Gomez · V. Rangel
Department of Electrical Engineering, National Autonomous University of Mexico, Mexico City, Mexico
e-mail: michael@fi-b.unam.mx;
michaelpascoemx@yahoo.com.mx

J. Gomez
e-mail: javierg@fi-b.unam.mx

V. Rangel
e-mail: victor@fi-b.unam.mx

M. Lopez-Guerrero
Department of Electrical Engineering, Metropolitan Autonomous University, Mexico City, Mexico
e-mail: milo@xanum.uam.mx

Published online: 20 February 2009

ad-hoc network. The number of intermediate nodes will depend on the distance between source and destination nodes, the transmission range and node density. Traffic relaying in mobile ad-hoc networks, however, is a difficult task. Node mobility, signal interference and power outages make the network conditions change frequently. As a result, any link along a route may fail at some point, forcing the nodes to find another route. It is clear that route duration strongly depends on the node mobility pattern, and that it would be convenient to compute this duration in advance.

Since to a large extent, the degree of mobility determines route duration, an analytical study of route duration is of crucial importance. Such a study can be used to anticipate route disruption and to avoid the degradation of system performance. Knowledge of route duration can be used to select an alternative route before the current one fails and it can also be used to decrease or limit packet losses and latency due to overhead signaling during route reconstruction. Because route duration decreases with route length, a route duration model could be used to scale the maximum network size up/down so as to meet minimum route duration requirements to ensure a satisfactory communication between any pair of nodes.

The main contribution of this paper is that it presents an analytical study that predicts the time duration of routes in mobile ad-hoc networks. The study presented in this paper can be used with different mobility models. Previous researchers have analyzed this issue, but their results have limited applicability. The approach hereby presented is much more powerful and has a higher applicability than other models as, it is not tied to any specific scenario or mobility pattern.

The rest of the paper is as follows: Sect. 2 presents a description of previous work in this area. A study of route duration of a 3-node route is presented in Sect. 3 for a case in which only the intermediate node moves. This analysis explores some factors that affect the route duration problem. Section 4 describes the procedure to obtain a route duration model, for routes with 3 mobile nodes, using two mobility patterns (Random WayPoint and Random Walk). In Sect. 5, the model is generalized in order to consider routes with N intermediate mobile nodes. Section 6 presents simulations using the NS-2 network simulator to compare the analytical model versus simulation results. Finally, the paper concludes with Sect. 7 in which our final remarks are presented.

2 Related work

Work related to route duration in MANETs falls into two different categories according to the method followed by the authors, the experimental or analytical category.

Under the experimental category, simulation has been the main method through which route duration properties of mobile ad-hoc networks were analyzed in the past. Simulation-based studies consider several parameters like the mobility model, the traffic pattern, the propagation model, etc. The authors in [3] carried out one of the first studies concerning the analysis of route duration based on empirical results obtained by simulations. These authors examined detailed statistics of route duration considering several mobility models, i.e., Random WayPoint (RWP) studied in [4], Reference Point Group Mobility (RPGM) described in [12], Freeway (FW) and Manhattan (MH) introduced in [2]. In [3] the authors observed that, under certain conditions (i.e., a minimum speed and routes with several hops), the time duration of routes can be approximated by exponential distributions. They evaluated the effect of the number of hops, the transmission range and the relative speed of the mobility model on route duration. However, the authors did not consider the goodness of fit of any other probabilistic model. Moreover, they did not justify the selection of an exponential distribution with any mathematical validation. To deal with this limitation, the authors in [11] used Palm's theorem to state that, under some circumstances (e.g., infinite node density), the lifetime associated to routes with a large number of hops converges to an exponential distribution. These works provide a solution for the analysis of paths which is valid only for routes with a large number of hops. Their study could thus not be applied to many practical MANET applications where paths consist of few hops only. In spite of these limitations, the popularity of the exponential fitting has been used as a common approximation in some other works such as in [1]. In [1], the authors presented a statistical model for estimating route expiration time adaptively, in order to reduce the control traffic of on-demand routing protocols.

Under the analytical category, there are several studies related to route duration in the literature. Even though the authors of these works followed different approaches to solve the route duration problem, these results are of limited applicability since they did not provide an expression for modeling duration of routes with several intermediate nodes. The authors in [6], for example, presented a simplified model of link duration for a single-hop case. Based on this model, they tried to generalize a model for a multi-hop route, but they did not provide any closed-form solution for it. In [10], the authors presented an analysis of link duration for a two-hop MANET. In this study, the authors considered an exponential distribution of route duration and assumed that the source and destination nodes are static while the intermediate node is moving using the RWP mobility model. However, they did not extend their analysis to routes with several hops. The authors in [15] assumed that link durations are independent and exponentially distributed random variables with a known mean link duration. Based on these assumptions, the authors derived some expressions to estimate route duration for single and multiple routes. However, in most cases, it cannot be assumed that the mean link duration value is a known parameter. In [19], the authors presented a framework for studying route duration in mobile ad-hoc networks based on various mobility models, but they did not present any detailed analytical expressions. The authors in [16] presented some analytic expressions to characterize various statistics, such as: link lifetime, new link inter-arrival time, link breakage inter-arrival time and link change inter-arrival time, by probabilistic and geometrical methods. The authors in [20] present statistical models to evaluate the lifetime of a wireless link in MANETs when nodes move randomly within constrained areas. Also in [20], it is shown that link lifetime can be computed through a two-state Markov model. In [17], the authors propose a new metric named *Mean Residual Path Lifetime* which they used as a criterion to select routes with longer route duration times instead of the minimum number of hops, which is a criterion commonly used in MANETs. The mobility model considered in [9] used fluid-flow techniques to analytically model the average sojourn time of an intermediate node while it crosses the region formed by the intersection of the coverage zones between its adjacent nodes (overlapping region). This model was the first one to take into consideration the shape and size of the overlapping region. In [9], the authors assumed that intermediate nodes are found right after entering the overlapping region. But they did not reflect on the possibility that the forwarding node is already located within this region, which is the usual case, so route duration estimated by this model would be very different from the real value. Although this model assumed various intermediate nodes, because it considered all overlapping regions have similar size, the actual sojourn time for each forwarding node in the route would be the same, thus route duration predicted by this model will be the same for routes with one or several intermediate nodes, which is not realistic. In [18], the authors derived the joint probability distribution of route duration using discrete-time analysis for the Random Walk (RW) model. They based their analysis of route duration partitioning the MANET network into a number of hexagonal cells and assuming that mobile nodes roam around in a cell-to-cell basis. In [21], the authors described the probability distribution function of route duration assuming that nodes move according to a constant velocity model and derived the statistics of link and route duration in ad-hoc networks. It is worth mentioning that the analytical works presented in [18] and [21] are the closest studies to ours, in the sense that they tried to approach the problem by analytical means only and they presented comparable performance metrics, such as route length (number of hops), transmission range, etc. In Sect. 6, we will present a comparison between these models and ours.

Although a study of route duration is extremely difficult to carry out even under simple mobility patterns, in this paper we present a route duration model aimed to remove some of the limitations found in previous works. It is important to point out that there is no general mobility model that foresees all possible dynamic behaviors of mobile nodes. The proposed model predicts the time duration of routes with an arbitrary number of intermediate nodes, the only assumption we make is that the PDF of route duration for a 3-node mobile case can be somehow obtained. This paper considers two mobility models commonly used in MANETs studies, i.e., RWP and RW.

3 Route analysis of 3-node routes

Before we approach the route duration problem, it is important to analyze and understand a simple route scenario first, where a 3-node route will be analyzed, considering that only the intermediate forwarding node is moving while source and destination nodes remain static. Developing this analysis will allow us to observe the impact different factors have on route duration in MANETs, including intermediate node's initial position and the size of the overlapping region.

Due to the fact that the actual number of possible shapes for a coverage zone is endless, the most sensible approach to model it is by means of a circular area. In most papers attempting to model route duration by simulation, empirical or analytical means make use of this assumption or they at least use regular areas (e.g., hexagonal). In this work, the transmission range of each node is assumed to be constant, thus leading to circular coverage zones, as shown in Fig. 1. Let us denote by R the transmission range.

In any route, intermediate nodes will be found inside the overlapping region formed by the intersection of the coverage zones between their adjacent route neighbors, see Fig. 1. As we stated before, the coverage zones are considered to be circular, thus leading to overlapping regions with an *oval-like* shape. Additionally, note that the size of the overlapping region changes for different intermediate nodes. Therefore, the sojourn time of a forwarding node within each region can thus vary significantly. To include these considerations in the analysis, it is necessary to consider all possible initial positions and trajectories of nodes in the route, as well as the different sizes of the overlapping regions. In order to illustrate this, in Fig. 1 we show a route from source node S to destination node D involving several forwarding nodes.

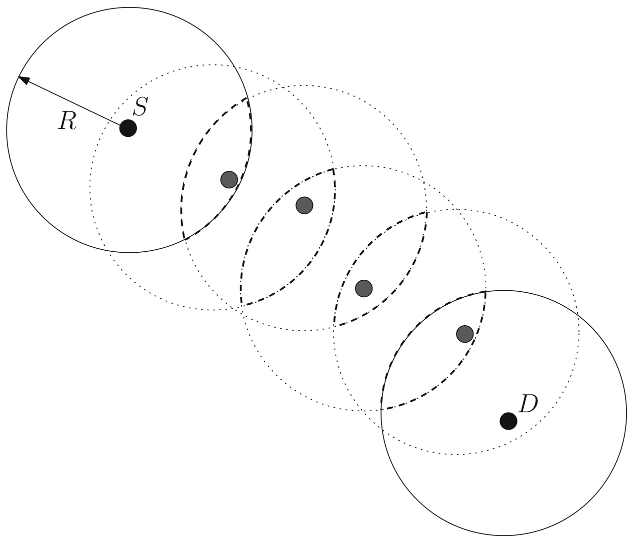

Fig. 1 Example of a route involving several intermediate nodes

Let us fix the source and destination nodes at points $S(x_S, y_S)$ and $D(x_D, y_D)$, respectively (as shown in Fig. 2). As we stated before, the coverage zone of each node has the shape of a circle with radius R. As illustrated in Fig. 2, factor h is an indicator of the size of the overlapping region, where $h = R - \frac{d_{S-D}}{2}$ and $d_{S-D} = \sqrt{(x_S - x_D)^2 - (y_S - y_D)^2}$ is the Euclidean distance between nodes S and D. This factor plays a crucial role in the operation and performance of routing protocols for wireless ad-hoc networks. As shown in Fig. 2, each intermediate forwarding node must be located within the overlapping region. Let points $A(x_A, y_A)$ and $B(x_B, y_B)$ be

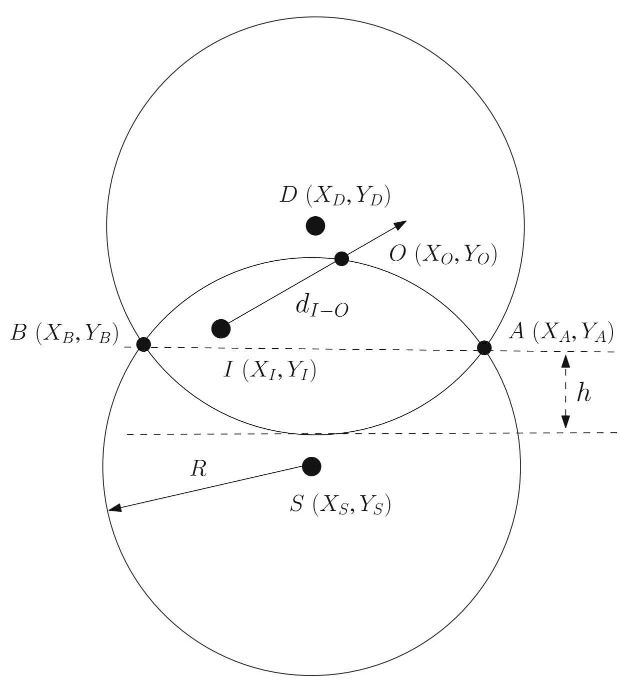

Fig. 2 Overlapping region of two adjacent nodes

the intersection points between both circles. It is easy to show that the coordinates of points A and B can be found by:

$$x_{A/B} = \frac{-B' \pm \sqrt{B'^2 - 4A'C'}}{2A'},$$

where x_A and x_B are the abscissas of points A and B. The coefficients A', B' and C' are given by:

$$\begin{aligned} A' &= 4[(x_S - x_D)^2 + (y_S - y_D)^2], \\ B' &= -4[(x_S^2 - x_D^2)(x_S - x_D) + (y_S - y_D)^2(x_S + x_D)], \\ C' &= [(x_S^2 - x_D^2) - (y_S - y_D)^2]^2 + 4(x_S^2 - R^2)(y_S - y_D)^2, \end{aligned}$$

and

$$y_{A/B} = \frac{2(x_D - x_S)x_{A/B} + (x_S^2 - x_D^2) + (y_S^2 - y_D^2)}{2(y_S - y_D)}$$

where y_A and y_B are the ordinates of points A and B.

As shown in Fig. 2, point $I(x_I, y_I)$ is the initial position of the intermediate node and point $O(x_O, y_O)$ is the position where this node leaves the overlapping region. In this section, we are considering that intermediate node is following a rectilinear trajectory sloped α_I degrees, measured with respect to the horizontal axis, and moving at constant speed v_I. The distance travelled by an intermediate node moving from I to O (d_{I-O}) can be found by geometric analysis as:

$$d_{I-O}(\alpha_I) = \left| -\sqrt{a^2 + b^2}\sin(\alpha_I + \delta) + \sqrt{R^2 - [(a^2 + b^2)\cos^2(\alpha_I + \delta)]} \right|. \quad (1)$$

Parameters a, b and δ, found in Eq. 1, must be computed separately to analyze the link between source node–intermediate node and the link between intermediate node–destination node. When the intermediate node crosses over the border of the source node coverage zone, parameters a, b and δ are:

$$a = y_I - y_S, \quad b = x_I - x_S \quad and \quad \delta = \arctan\left(\frac{b}{a}\right)$$

otherwise

$$a = y_I - y_D, \quad b = x_I - x_D \quad and \quad \delta = \arctan\left(\frac{b}{a}\right).$$

Then, the average distance travelled by an intermediate node before leaving the overlapping region ($\overline{d}_{I-O}$), given its initial position $I(x_I, y_I)$, can be found using the Mean Value Theorem [14], this is:

$$\overline{d}_{I-O} = \frac{1}{\Delta\alpha_I}\int_{\alpha_m}^{\alpha_M} d_{I-O}(\alpha_I)d\alpha_I, \quad (2)$$

where

$$\Delta\alpha_I = |\alpha_M - \alpha_m|,$$

$$\alpha_M = \arctan\left(\frac{y_B - y_I}{x_B - x_I}\right), \quad \alpha_m = \arctan\left(\frac{y_A - y_I}{x_A - x_I}\right)$$

and

$$\alpha_M = \arctan\left(\frac{y_A - y_I}{x_A - x_I}\right), \quad \alpha_m = \arctan\left(\frac{y_B - y_I}{x_B - x_I}\right).$$

Therefore, the average distance travelled by an intermediate node before leaving the overlapping region would be:

$$\overline{d}_{I-O} = \frac{1}{\Delta\alpha_I}\left[\sqrt{a^2+b^2}\cos(\alpha_I+\delta)|_{\alpha_I=\alpha_m}^{\alpha_I=\alpha_M} + \int_{\alpha_m}^{\alpha_M}\sqrt{R^2-[(a^2+b^2)\cos^2(\alpha_I+\delta)]}d\alpha_I\right]. \quad (3)$$

In this analysis, we consider the angle α_I as an independent random variable uniformly distributed over the interval ($\Delta\alpha_I$) given by the difference between its maximum and minimum values (α_M and α_m, respectively). As well as the parameters a, b and δ, the angles α_m and α_M, must be computed separately for the link between source node–intermediate node and for the link between intermediate node–destination node.

Figure 3(a), (b) show the angles involved in the links between source node–intermediate node and intermediate node–destination node, respectively. Figure 3(c) shows some trajectories followed by an intermediate node from its initial to final positions. Each line in Fig. 3(c) represents a different trajectory.

Because it does not seem possible to integrate Eq. 3 algebraically, we use an approximation by replacing the square root in the integrand with a binomial series [14] and, after some algebra, it can be simplified as shown:

$$\sqrt{R^2-[(a^2+b^2)\cos^2(\alpha_I+\delta)]} \approx R\left(1-\sum_{j=1}^{\infty}k_j(u(\alpha_I))^j\right)$$

where

$$u(\alpha_I) = \cos^2(\alpha_I+\delta)$$

and

$$k_j = \frac{1}{(j)!}\left(\frac{a^2+b^2}{R^2}\right)^j\left[\prod_{l=1}^{j}\left(\frac{3}{2}-l\right)\right]$$

then

$$R\int_{\alpha_m}^{\alpha_M}\left(1-\sum_{j=1}^{\infty}k_j(u(\alpha_I))^j\right)d\alpha_I = R\left(\alpha_I|_{\alpha_m}^{\alpha_M} - \sum_{j=1}^{\infty}k_j\int_{\alpha_m}^{\alpha_M}\cos^{2j}(\alpha_I+\delta)d\alpha_I\right). \quad (4)$$

The range of convergence for the binomial series used in the previous approximation is given by $(a^2+b^2) < R^2$. It is worth mentioning that the accuracy of the approximation is degraded as $(a^2+b^2) \rightarrow R^2$, which corresponds to the case when the nodes are located very close to the boundary of the overlapping region. In this case the approximation has to be used with care.

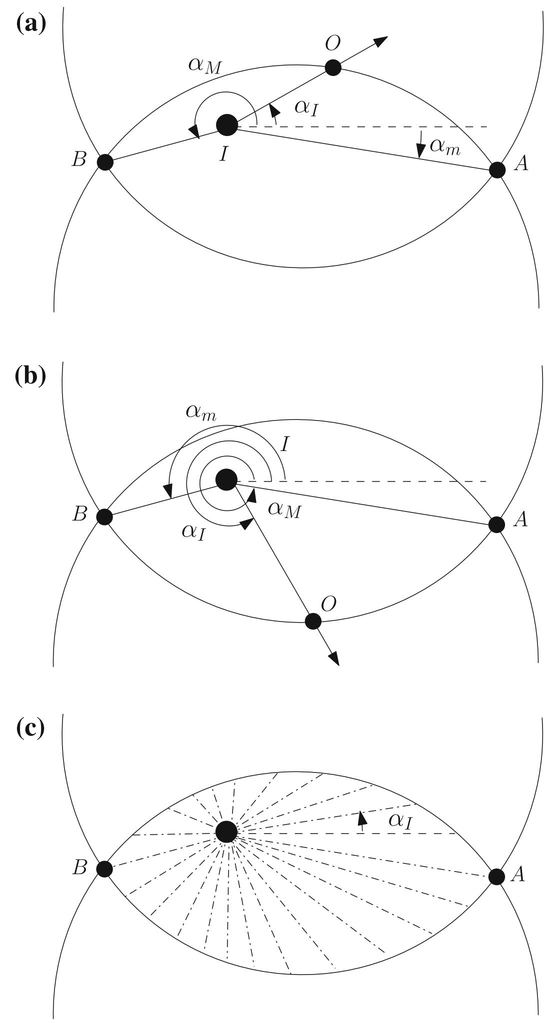

Fig. 3 **a** Angles involved while modeling link duration of source–intermediate node. **b** Angles involved while modeling link duration of intermediate node–destination. **c** Some trajectories followed by an intermediate node from its initial to final positions

After replacing the integral found in Eq. 3 by 4, an approximation of the average distance will be:

$$\overline{d}_{I-O} \approx \frac{1}{\Delta\alpha_I}\left[\sqrt{a^2+b^2}\cos(\alpha_I+\delta)|_{\alpha_I=\alpha_m}^{\alpha_I=\alpha_M} + R\left(\alpha_I|_{\alpha_m}^{\alpha_M} - \sum_{j=1}^{\infty}k_j\int_{\alpha_m}^{\alpha_M}\cos^{2j}(\alpha_I+\delta)d\alpha_I\right)\right]. \quad (5)$$

The average sojourn time for a forwarding node within the overlapping region (T_I) is directly proportional to the average distance travelled by the intermediate node ($\overline{d}_{I-O}$), and inversely proportional to its speed of movement (v_I). Therefore:

$$T_I = \frac{\overline{d}_{I-O}}{v_I}. \tag{6}$$

This sojourn time defines the route duration for the 3-node route.

In Eq. 5 we can remove dependence on the initial position $I(x_I, y_I)$ by averaging the distance over all possible initial positions within the overlapping region, i.e.,

$$\overline{D}_{I-O} = \int_{y_m}^{y_M} \int_{x_m}^{x_M} f_{x_I y_I}(x_I, y_I) \overline{d}_{I-O}(x_I, y_I) dx_I dy_I \tag{7}$$

where $f_{x\_I}y_I\,(x_I, y_I\,)$ represents the joint probability density function for the random variables x_I and y_I. This PDF depends on the spatial layout of intermediate nodes.

In order to illustrate the impact of the intermediate node's position on 3-node route duration, we conducted a series of calculations, using previous equations to evaluate the average distance ($\overline{d}_{I-O}$) and its standard deviation (σ_{I-O}) for a set of 1,000 intermediate forwarding nodes randomly placed in different positions inside the overlapping region. For each forwarding node, the average distance is obtained by using Eq. 5 and the standard deviation is evaluated using 3,600 values of the travelled distance obtained by Eq. 1. Each node was considered to move along 3,600 rectilinear trajectories, with a 0.1° difference. Figure 4(a), (b) show the average distance ($\overline{d}_{I-O}$) and its standard deviation (σ_{I-O}), respectively. The *oval-like* shape on the XY plane of Fig. 4(a), (b) represents the overlapping region. In these figures, it is clear that the values of average distance and standard deviation depend on the position where the forwarding node is initially located. The closer the intermediate node is found to the border of the overlapping region, the lower the average distance (i.e., shorter route duration), and the higher its standard deviation. This behavior can be explained because, whenever the forwarding node is close to the boundary of the region, it will experience either very short times (i.e., when it leaves the overlapping region right away) or long times (i.e., when it crosses a large section of the overlapping region before leaving it).

We conducted similar tests considering four regular shapes of the overlapping region (i.e, oval, square, circular and rectangular) with equal areas. We found the same trends as the ones depicted in Fig. 4(a), (b). However, independently of the shape, the bigger the overlapping region the longer the average sojourn time of the intermediate node in the overlapping region.

From the 3-node static case, we can conclude that the initial positions of source, intermediate and destination nodes impact route duration in MANETs. Also, the size of the overlapping region is a crucial factor that affects route duration. This justifies that route duration analysis should include node position and overlapping region size.

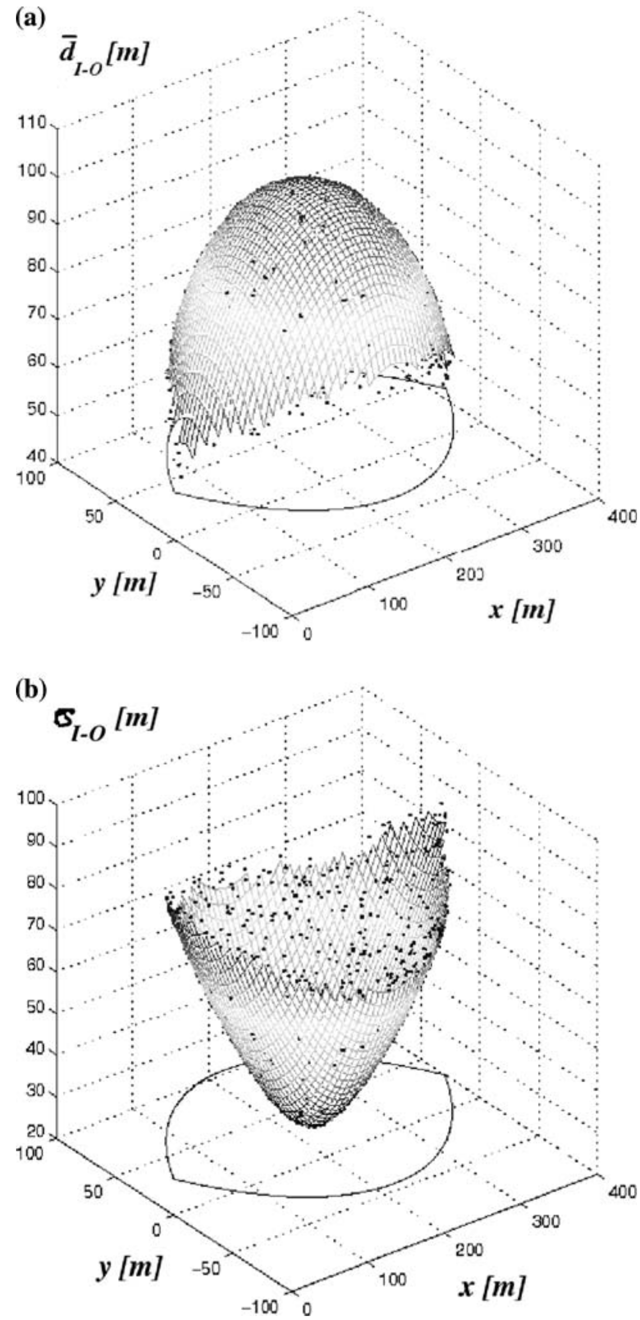

Fig. 4 **a** Average distance distribution as a function of the initial position of the intermediate node. **b** Standard deviation distribution as a function of the initial position of the intermediate node

4 Route duration model

As described above, each intermediate node must be found inside the respective overlapping region, formed by the intersection of the coverage zones between their adjacent route neighbors, see Fig. 1. In this work, we consider that the coverage zone is circular and all nodes use the same transmission range (R meters). Note that the size of each overlapping region changes for different intermediate nodes, thus the sojourn time of each intermediate node within this region can vary significantly. To include all these considerations in the analysis, it would be necessary to consider the mobility model that describes the movement behavior followed by mobile nodes in the network. It would also be necessary to take into consideration all possible initial positions and node trajectories. It is clear that to note this would imply an extremely complex analysis because the size and location of the overlapping region are constantly changing as time passes in a mobile ad-hoc network.

Figure 1 shows a multi-hop route from a source node *S* to a destination node *D* involving several forwarding nodes. Each circle in Fig. 1 represents the constant transmission range for each node in this route.

In this paper, we follow a method in which we first compute the PDF of route duration for routes formed by 3 mobile nodes only (*triplets*). Section 5 shows a general method to obtain the average route duration of routes formed by *N* intermediate mobile nodes.

4.1 PDF for routes with 3 mobile nodes

We here analyze 3-node routes with all mobile nodes. Based on this specific scenario, we analyze how the relative movement of nodes affects route duration. We then determine the Probability Density Function (PDF) that describes the probability that a 3-node route could last a time longer than a given value. Based on this PDF, it is possible to find the average route duration for routes formed by several intermediate nodes, as will be shown in Sect. 5. This PDF can be determined by analytical or statistical methods depending on the mobility model followed by mobile nodes in the network.

In this section, we model how long it takes for the intermediate node to exit the overlapping region. But, in this case, we consider all nodes to be moving according to a random-based mobility model. In this kind of model, mobile nodes move randomly and freely without any restriction. To be more specific, the speed, destination and/or trajectory are all chosen randomly, independent from other nodes. This kind of model has been used in many simulation studies. In this section, we consider two random-based mobility patterns, i.e., the Random WayPoint and Random Walk models. However, other mobility patterns can also be considered, as long as the associated route duration PDF is provided.

4.1.1 Random WayPoint

Due to its simplicity and wide availability in network simulators, the Random WayPoint Model (RWP) is one of the mobility models most commonly used to evaluate MANET performance. For instance, in the *network simulator NS-2* [8], the *setdest* tool may be used to generate RWP traces. There are two versions of this tool. In version 1, various parameters are established, i.e., the number of mobile nodes, pause time, maximum speed, simulation time and size of the simulation field. In version 2, other parameters are added or changed, i.e., speed type, minimum and maximum speeds and pause type.

The implementation of this mobility model is as follows: as the simulation starts, all nodes are randomly placed within the network area. Then, each mobile node randomly selects one location in the simulation field as the first destination point. It then travels towards this destination point with a constant velocity chosen uniformly and randomly from $[0, V_{max}]$ or $[V_{min}, V_{max}]$ (depending on the setdest version), where the parameters V_{min} and V_{max} are the minimum and maximum allowable velocities for every mobile node, and $V_{min} < V_{max}$. The velocity and direction of each node are chosen independently from other nodes. Upon reaching its destination point, each node stops for an interval, defined by the *pause time* parameter T_{pause}. If $T_{pause} = 0$, this leads to continuous mobility. As soon as the pause time expires, each node chooses another destination point and moves towards it with a different speed. The whole process is repeated again until the simulation ends.

It is important to point out that the scenarios considered in this work can be made more complex in many different ways. In this work, however, we have mainly attempted to study the effect of mobility patterns and spatial layout of nodes on route duration. For this reason, we did not conduct experiments with heterogeneous speeds since we consider that, by itself, this is material of future work. Nevertheless, at this point we would like to mention that other authors have investigated this very same issue in the cases where each node chooses a speed at random between V_{min} and V_{max}. For instance, the authors in [13], calculated $\overline{M}$ as the measure of relative speed averaged over all node pairs and over all time. Using this mobility metric, it is possible to roughly measure the level of nodal speed and differentiate the different mobility scenarios based on the level of mobility. Additionally, the authors of [2] showed that the *Average Relative Speed* increases linearly and monotonically with the maximum allowable speed. Based on these results we speculate that our scenario would be equivalent to one with random speed and an average relative speed whose value equals the constant value we used.

4.1.2 Random Walk

The Random Walk Model (RW) has similarities with the RWP model because the node movement has strong randomness in both models. However, in the RW model, nodes change their speed and direction at specific intervals only. In the RW model, each change of trajectory occurs after a fixed time interval t_x or after a fixed traveled distance d_x, at the end of which a new direction and speed are calculated. For every new interval, each node randomly and uniformly chooses its new direction $\theta(t)$ from (0, 2π]. In a similar way, the new speed $v(t)$ follows a uniform distribution or a Gaussian distribution within [V_{min}, V_{max}]. Therefore, during the interval, a node moves with a velocity vector ($v(t)\ cos\ \theta(t)$, $v(t)\ sin\ \theta(t)$). Also, there is a discrete version of the RW mobility model where the trajectory randomly changes among four different angles only, [0, π/2, π,3π/ 2]. This version can be used to emulate a node moving on a reticulated area.

The RW model is a memory-less process, because the information about the previous status is not used for future trajectory decisions. That is to say, the current velocity is independent from the previous velocity and the future velocity is also independent from the current velocity. However, that is not the case of mobile nodes in many real life applications.

4.1.3 PDF generation

As aforementioned, we need to model how long it takes for the intermediate node to exit the overlapping region in a 3-node route. But, in this case, we consider that all nodes in the 3-node route move according to a random-based mobility model (RWP or RW mobility models). Let us identify the source, intermediate and destination nodes with indexes S, I and D, respectively. Let us denote such index with k, thus $k = S,\ I$ or D. Each node's position is described by the coordinates $(x_k(t), y_k(t))$. Let $\vec{v}_k(t)$ be the velocity vector of node k, i.e.,

$$\vec{v}_k(t) = [v_{x_k}(t)]\hat{\imath} + \left[v_{y_k}(t)\right]\hat{\jmath} \tag{8}$$

where $\hat{\imath}$ and $\hat{\jmath}$ are the unit vectors.

Each node k moves according to a random-based mobility model, then it follows a trajectory sloped at α_k degrees and it moves at a speed v_k for a period of time that depends on the mobility model (for the RWP model, any node keeps moving with the same direction and speed upon reaching its destination; for the RW model, any node keeps moving with the same direction and speed for a constant travelled distance). The behavior of α_k and v_k, as time passes, would be described according to the selected mobility model. Then, the velocity vector for node k ($\vec{v}_k(t)$), would be given by:

$$\vec{v}_k(t) = [v_k \cos(\alpha_k)]\hat{\imath} + [v_k \sin(\alpha_k)]\hat{\jmath} \tag{9}$$

where

$$|\vec{v}_k(t)| = v_k \qquad [m/s].$$

Now, let $\vec{r}_k(t)$ be the vector that describes the position of node k, that is:

$$\vec{r}_k(t) = \vec{r}_k(0) + \int_o^t \vec{v}_k(t)dt \tag{10}$$

where the initial vector position of node k, $\vec{r}_k(0)$ is given by $\vec{r}_k(0) = x_k(0)\hat{\imath} + y_k(0)\hat{\jmath}$.

It is important to point out that in the general case, the slope of trajectory, given by α_k, is not constant with respect to t. However, in this analysis we are considering that the probability of having direction changes is negligible (a node moving in the overlapping region will not change its current direction). If direction changes are rare events, α_k can be considered as constant in the analysis of a node roaming in the overlapping region and Eq. 10 reasonably holds.

Substituting Eq. 9 in 10, we get:

$$\vec{r}_k(t) = [v_k t\cos(\alpha_k) + x_k(0)]\hat{\imath} + [v_k t\sin(\alpha_k) + y_k(0)]\hat{\jmath}, \tag{11}$$

which can be represented by

$$\vec{r}_k(t) = [x_k(t)]\hat{\imath} + [y_k(t)]\hat{\jmath}, \tag{12}$$

where

$$x_k(t) = v_k t\cos(\alpha_k) + x_k(0)$$

is the abscissa of position of node k and

$$y_k(t) = v_k t\sin(\alpha_k) + y_k(0)$$

is the ordinate of position of node k.

Now, let $d_{S-I}(t)$ be the distance between the source and intermediate nodes and let $d_{I-D}(t)$ be the distance between the intermediate and destination nodes. Distances $d_{S-I}(t)$ and $d_{I-D}(t)$ can be found by the Euclidean distance formula, so:

$$d_{S-I}(t) = |\vec{r}_I(t) - \vec{r}_S(t)| \tag{13}$$

$$d_{I-D}(t) = |\vec{r}_D(t) - \vec{r}_I(t)|. \tag{14}$$

When either distance $d_{S-I}(t)$ or $d_{I-D}(t)$ exceeds the transmission range (R), the communication between the respective adjacent node pair [S, I] or [I, D] is interrupted. Route disruption happens when either:

$$d_{S-I}(t) \geq R \tag{15}$$

or

$$d_{I-D}(t) \geq R. \tag{16}$$

Let $T_{[S,\ I]}$ and $T_{[I,\ D]}$ be the rupture time of communication between adjacent node pairs [S, I] and [I, D], respectively. Then, route duration time (T_I), for a 3-node route, will be found by:

$$T_I = \min\left(T_{[S,I]}, T_{[I,D]}\right). \tag{17}$$

Figure 5 illustrates the position and velocity vectors of a route with 3 mobile nodes (source *S*, intermediate *I* and destination *D*). This figure shows the position of the corresponding nodes (*S*, *I* and *D*) at instant *t* when each node moves in the direction described by its velocity vector.

In order to get an average value of route duration for any route, it would be necessary to consider all possible trajectories and initial positions for the three nodes involved in the route. It is clear to note that this case is far more complex to analyze than the 3-node static case because the size and location of the overlapping region are constantly changing as time passes and, consequently, the factor *h* varies in the same way.

Route duration is given by the minimum time that each forwarding node remains inside of its associated overlapping region (using Eq. 17. In order to obtain a mathematical model to calculate the average duration of a given route formed by 3 nodes, we constructed different histograms using the data provided by Eq. 17. Each histogram represents the relative frequency of time durations of a set of routes for a specific initial *h* value which corresponds to a particular overlapping region. Additionally, each histogram considers all possible initial positions of the intermediate node and all the possible initial trajectories followed by the three nodes, according to the selected random-based mobility model.

In this study, we analyze the cases for three initial *h* values corresponding to different overlapping regions. These values are $h = R/10, 0.28R, R/2$ [*m*]. An overlapping region with an initial $h = R/10$ takes into account an overlapping region with a small size. On the other hand, an overlapping region with $h = R/2$ represents the maximum size of the overlapping region. Finally, $h = 0.28R$ [*m*] corresponds to a typical overlapping region. The later value was obtained by means of an exhaustive analysis of 10,000 routes formed by 3 nodes (*triplets*). These routes were selected from all possible *triplets* found from a set of nodes randomly placed into several network scenarios with different size and node densities. The *triplets* were discovered using the Dijkstra's Shortest Path Algorithm [7]. The shortest route between any pair of the nodes will be formed by the set of intermediate nodes with the minimum number of links (hops). The routes discovered by this procedure are independent from any routing protocol or simulation software. In fact, it is expected that an efficient routing protocol will find such routes.

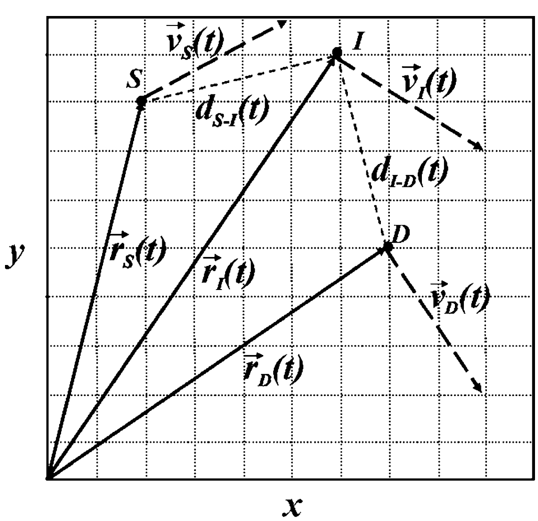

Fig. 5 Position and velocity vectors for source, intermediate and destination nodes

In order to obtain these histograms, we developed a statistical analysis, following this procedure: (1) At time zero, we selected source and destination nodes so the size of the overlapping region (described by the factor *h*) was constant. (2) A node was randomly placed as forwarding node between source and destination. (3) We assigned random trajectories (described by a random-based mobility model) for the three nodes involved and let the nodes move at a constant speed $v_k = 1$ [*m*/*s*]. (4) We used Eq. 6 to calculate the instant when the distance between either source-forwarding nodes or forwarding-destination nodes exceeded the transmission range *R*. (5) we repeated the same procedure 10,000 times for multiple positions and trajectories of the three nodes. This number of experiments was necessary in order to obtain an experimental PDF function whose statistical properties did not change significantly with more experiments. However, we found that performing more experiments did not significantly change the results.

In Fig. 6(a)–(c), we show the histograms for the three different values of *h* for the RWP mobility model. Each histogram graphically summarizes and displays the relative distribution of the data set provided by Eq. 17. The vertical axis of each histogram represents the relative frequency (the number of data that corresponds to a specific route duration time interval divided by the total number of data). The horizontal axis of each histogram corresponds to the route duration time, divided into intervals of 1 second each. As shown in Fig. 6(a)–(c), there is a relationship between the size of the overlapping region and the relative frequency of route duration times. Longer route duration happens more frequently when the overlapping region is larger. In a similar way, in Fig. 7, we show the histogram for a typical *h* value ($h = 0.28R$ [*m*]) but for the RW mobility model.

These histograms can be converted to Probability Density Functions (PDFs). We use a curve fitting method to find the mathematical expression that represents these PDFs. For the RWP mobility model, we selected two truncated Gaussian distributions. On the other hand, for the RW mobility model, we use two exponential distributions.

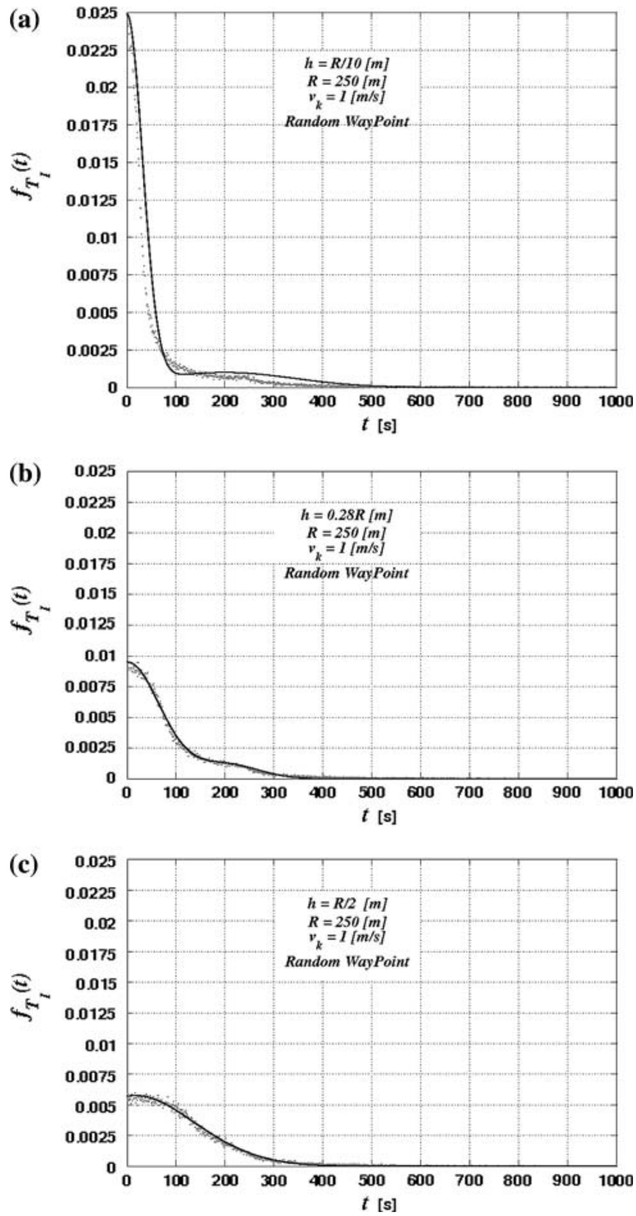

Fig. 6 Results with the Random WayPoint mobility model (**a**) PDF for $h = R/10$ [m], (**b**) PDF for $h = 0.28R$ [m], (**c**) PDF for $h = R/2$ [m]

These distributions were used as it was experimentally found that they accurately represent the histograms (see solid curves in Figs. 6(a)–(c), 7). Based on these distributions, the PDFs could be expressed as:

$$f_{T_l}(t) = \alpha_1 e^{-\left(\frac{t-\beta_1}{\delta_1}\right)^2} + \alpha_2 e^{-\left(\frac{t-\beta_2}{\delta_2}\right)^2}; \quad t > 0[s] \tag{18}$$

or

$$f_{T_l}(t) = \alpha_1 e^{-\beta_1(t)} + \alpha_2 e^{-\beta_2(t)}; \quad t > 0[s] \tag{19}$$

The first curve fitting corresponds to the RWP mobility model. where, parameters α_i, β_i and δ_i, for $i = 1{,}2$, were

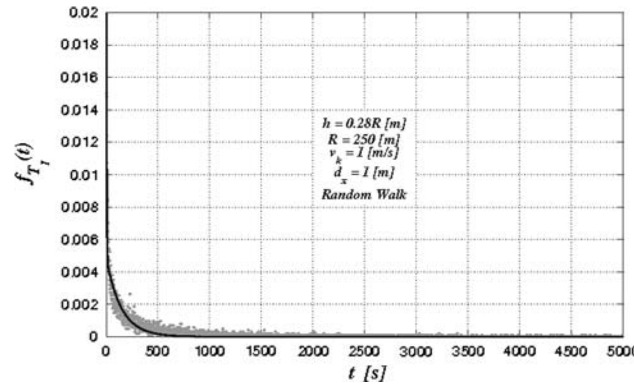

Fig. 7 Probability Density Function for $h = 0.28R$ [m] using RW

found by using the Robust Non-Linear Least Squares Fitting Method applying the Trust-Region Algorithm. A parameter of goodness of fit for this curve fitting method is: *R-Square* $\approx$ 0.99. Table 1 shows the values of the statistical parameters α_i, β_i and δ_i obtained for three initial values of $h = \{R/10, 0.28R, R/2\}$ [m]. The second curve fitting corresponds to the RW mobility model. where, parameters α_i and β_i, for $i = 1{,}2$ were found by using the same method. Table 2 shows the values of the statistical parameters α_i and β_i obtained for an initial value of $h = 0.28R$ [m]. Given a different initial h value, it is possible to find its parameters.

It is important to point out that this model considers all possible initial positions of the forwarding node and all possible initial trajectories followed by the source, intermediate and destination node, for a specific h value when the route was created.

From this section, we can conclude that the 3-node mobile case allows us to observe how the relative movement between source, intermediate and destination nodes affects route duration in MANETs.

Table 1 Statistical parameters for PDFs for RWP model shown in Fig. 6(a)–(c)

PDFs statistical parameters						
h [m]	α_1	β_1	δ_1	α_2	β_2	δ_2
$R/2$	0.0050	0.0000	155.00	0.0013	125.00	160.00
$0.28R$	0.0095	0.0000	95.000	0.0012	200.00	95.00
$R/10$	0.0245	0.0000	45.000	0.0010	200.00	200.00

Table 2 Statistical parameters for PDFs for RW model shown in Fig. 7

PDFs statistical parameters				
h [m]	α_1	β_1	α_2	β_2
$0.28R$	0.00515	0.05867	0.00068	0.00096

5 Route analysis of K-node routes

The previous section showed how the relative movement between source, intermediate and destination nodes affects route duration in MANETs. Finally, in this section, we will analyze a general case considering a route formed by K nodes, $K \geq 3$.

For convenience, we will not use the notation of nodes that we used previously. Each node will be identified by an integer number k, ($k = 0,1,2,\ldots,K-1$, where the source node is $k = 0$ and the destination node is $k = K-1$). Thus, the route will have $N = K-2$ intermediate nodes. Therefore, we could use Eq. 17 to calculate the time interval during which each forwarding node remains inside its associated overlapping region, but replacing the indexes S, I and D for the corresponding k values of each node of the N *triplets* and by computing route duration as the minimum value of the N time intervals. This case, however, would be even more complex to analyze than a 3-node case because the overlapping region associated to each intermediate node has a different size and position that are changing as time passes.

In order to simplify the analysis of routes involving N intermediate nodes, we propose a method to estimate the average route duration for a route formed by K nodes by taking N samples of a single PDF, defined by Eq. 18 or 19 and using the typical overlapping region size only ($h = 0.28R$ [m]). By using this method, we are assuming that the times that the intermediate nodes remain in their overlapping regions are mutually independent. Therefore, it is valid to divide the route into N simpler 3-node-mobile routes or *triplets*.

The PDF samples generate N random variables, given by $[T'_1, T'_2, \ldots, T'_N]$. Then, we compute the duration of a route involving K nodes, T'_{R_K}, as:

$$T'_{R_K} = \min\left(T'_1, T'_2, \cdots, T'_n, \cdots, T'_N\right). \qquad (20)$$

$$n = 1, 2, \ldots, N; \qquad N = K-2$$

where

T'_n: are independent and identically distributed random variables, each one representing the time that the intermediate node remains in its corresponding overlapping region.
n: identification number of each intermediate node.
N: maximum number of intermediate nodes in the route.

We developed an exhaustive study for different routes with N intermediate nodes using Eq. 20 and we estimated the average route duration on each case. In the following section, we show the results obtained from this study. We also demonstrate the precision of the proposed method, by comparing it with simulations and other analytical models found in the literature.

We should say that another method to compute route duration would be to select a different PDF associated to the exact h value for each intermediate node in the route and then sample it. However, we found that sampling one PDF only, with a typical h value ($h = 0.28R$ [m]), provides a good precision compared with simulations.

We also performed experiments with a model consisted of 3 PDFs related to the h values $R/10$, $0.28R$ and $R/2$. We found that, using a 3-PDF model, slightly increases the precision of the average route duration computation. We, therefore, consider that using this method is not justified because it has a higher complexity with a negligible improvement.

6 Simulation and results

Before showing the results we obtained from the proposed model, we want to show some tests we developed to verify how the NS-2 network simulator behaves. First, we started a simulation test, without any modification, to verify that the intermediate nodes, chosen by the routing protocol as forwarding nodes in routes of three nodes, were randomly distributed within the overlapping region. In these simulations we used Ad-hoc On Demand Distance Vector (AODV) as the routing protocol. Figure 8(a) graphically shows the random location of forwarding nodes (each intermediate node is represented by a little circle).

We then performed a series of simulation tests to validate the proposed model. Several scenarios were created using the NS-2 simulator. The simulation settings consisted of a network in a rectangular area with the following dimensions $X_{sc} = 2000$ [m] and $Y_{sc} = 2000$ [m] with 400 nodes. In this case, we considered the transmission range defined by the IEEE 802.11 standards (i.e., $R = 250$ [m]). Table 3 summarizes the main parameters of our simulation scenarios.

6.1 Simulation and results with random WayPoint

We selected a large network size to minimize the probability of having trajectory changes in any intermediate node within the overlapping region while they move according to the RWP mobility model. The probability that an intermediate node changes its trajectory within its associated overlapping region, can be found by: $P_I = \frac{A_{or}(h)}{A_{sc}}$, where $A_{or}(h) = 2R^2 arccos(\frac{R-h}{R}) - 2(R-h)\sqrt{R^2 - (R-h)^2}$ is the area of the overlapping region and $A_{sc} = X_{sc}Y_{sc}$ is the rectangular area of the scenario. If we consider our network settings, we would have $P_I < 1\%$.

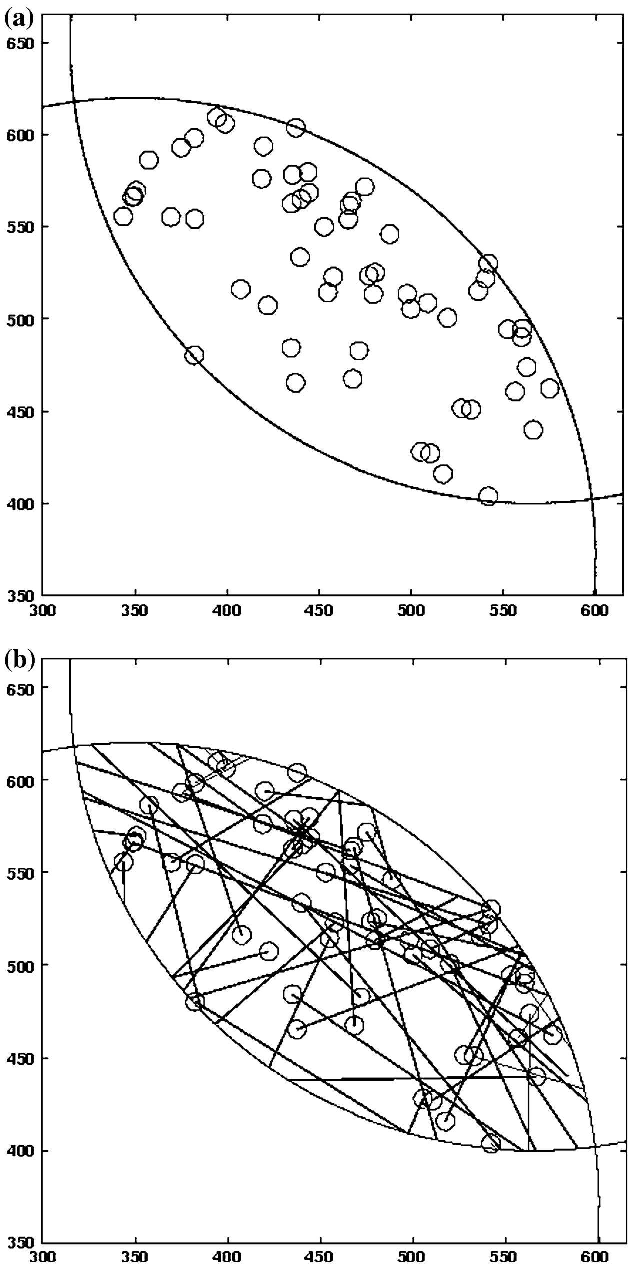

Fig. 8 **a** Spatial layout of initial positions of some intermediate nodes. **b** Trajectories followed by each intermediate nodes according to RWP mobility model

We simulated 3-node static and mobile cases by placing source and destination nodes with a fixed initial position, such that $h = (0.28)R$. As explained before, this value of h represents a typical overlapping region. Finally, we registered how long it took for a set of intermediate nodes, chosen randomly as forwarding nodes, to leave the overlapping region. Figure 8(b) shows the initial positions and trajectories followed by each intermediate forwarding node before leaving the overlapping region in a 3-node route, when source and destination are static. The initial positions are represented by little circles and trajectories are represented by line segments with variable length. From Fig. 8(b), it is clear to note that the initial positions and trajectories of the intermediate nodes, as well as the size of the overlapping regions are among the factors affecting route duration.

Table 3 Simulation parameters

Simulation parameters	
Parameter	Value
Range of transmission (R [m])	250
Simulation area length (X_{sc} [m])	2000
Simulation area width (Y_{sc} [m])	2000
Number of nodes (M)	400
Routing protocol	AODV
Mobility models	RWP / RW
Speed (v_k [m/s])	1

We developed another set of simulations in order to discover several routes involving K mobile nodes with N intermediate nodes while moving according to the Random WayPoint mobility model. We then let the simulation run until the first intermediate node left the route and we registered the time interval the route was available (i.e., $T_R = T_F - T_D$; where T_R: route duration time, T_F: route failure time, T_D: route discovery time). We performed 1,000 simulations using these routes to obtain sufficient data to validate the proposed model. We used the results provided by this set of simulations to generate the simulation curve presented in Fig. 9.

From Fig. 9, we can see that relative errors between the proposed model and simulation data were found around 20% for routes with 2 intermediate forwarding nodes, whereas relative errors oscillated between 6% and 3% for routes with 4, 8 and 16 intermediate nodes. We consider that the main reason why relative errors are larger for routes with small N is due to the variability of overlapping regions at time zero that we did not consider, since, we only used a typical value of h in the model; whereas relative errors for routes with larger values of N are smaller because the average h value for their overlapping regions is closer to the typical value we used. It is important to point out that the fact of having a maximum margin of error of 20% may be acceptable for many applications due to the complexity of this problem. As we expected, Fig. 9 shows that the time duration of routes decreases as the number of intermediate nodes increases. It is important to point out that the precision improves as the number of intermediate nodes increases.

In addition, Fig. 9 compares the results presented in this study with the analytical model presented by Yu et al. [21]. We selected this study, because we considered that the authors were addressing the same problem and provided a solution through different approaches. They also presented

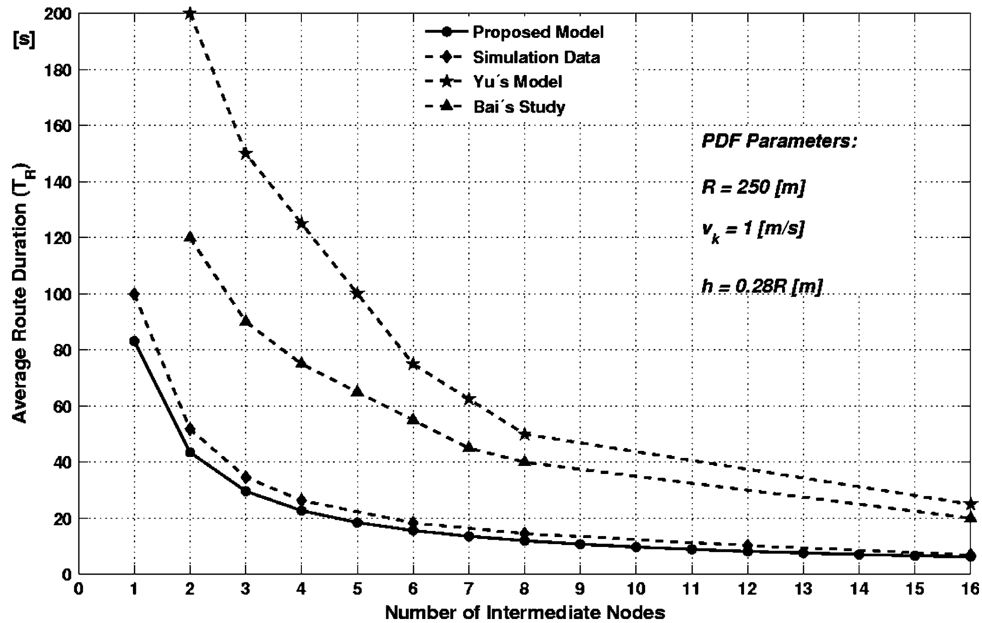

Fig. 9 Average route duration versus number of intermediate nodes for Random WayPoint mobility model

analytical expressions and displayed curves related to route duration, so they can be easily compared with our model. In [21], Yu et al. provided a graph with normalized values of average route duration time versus number of hops in the route. In this study, the authors indicated that normalized values of average route duration time must be multiplied by factor (R/v) to adjust them to any specific scenario. A comparison between this analytical study and our model is presented in Fig. 9. Figure 9 clearly shows that the proposed model has a greater accuracy than the one in [21].

Also, in Fig. 9 we compare the proposed model with the empirical study presented by Bai et al. in [3]. In [3], the authors propose an approximate function to estimate route duration (i.e., $T_R \approx \frac{R}{(\lambda_0 N_h v)}$; where T_R: route duration, R: transmission range, λ_0: experimental parameter (determined by network layout, node density and other parameters related to mobility models or scenarios), N_h: number of hops, v: speed) but they did not justify this function with any mathematical means. A comparison between this experimental study and our model is also shown in Fig. 9. It is clear that the proposed model has better accuracy than the function proposed in [3].

To give more validity to the proposed model and results, we repeated previous simulations but with a higher node density scenario (i.e., 1000 [m] × 1000 [m] network with 300 nodes). It is important to note that we obtained consistent results with this simulation scenario within 5% variations with respect to the results shown in Fig. 9.

6.2 Simulation and results with Random Walk

In a similar way, we also developed a set of simulations in order to discover several routes involving K mobile nodes with N intermediate nodes while moving according to the RW mobility pattern. Also, we let the simulation run until the first intermediate node left the route and we registered the time interval the route was available. We performed the same number of simulations (1,000 simulations) using these routes to obtain sufficient data to validate the proposed model. We used the results provided by this set of simulations to generate the simulation curve presented in Fig. 10.

In Fig. 10, we compare our results with the analytical model for RW mobility pattern presented by Tseng et al. Briefly, in [18], the authors presented a graph with the expected values of route duration versus route length and we used these results to compare them with our model and simulations. A comparison between this analytical study and the proposed model is presented in Fig. 10. Clearly, it shows that the proposed model outperforms the one provided by [18].

7 Conclusions

In this paper, we proposed a model to estimate route duration in wireless ad-hoc networks when nodes move according to a random-based mobility model. This model analyzes a route formed by N intermediate nodes. First, we approached this problem by studying simpler 3-node routes. From the 3-node static case, we demonstrated that the initial positions of source, intermediate and destination nodes have a great impact on route duration in MANETs. From the 3-node mobile case, we were able to obtain the PDF of route duration of 3-node routes for Random WayPoint and Random Walk models. Finally, we showed

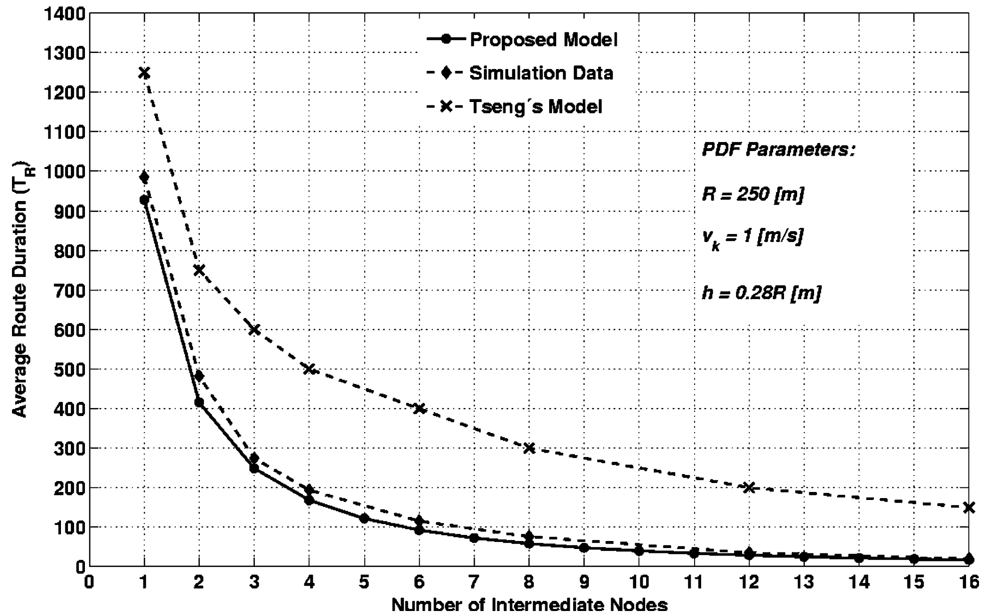

Fig. 10 Average route duration versus number of intermediate nodes for Random Walk mobility model

that, regardless of the mobility pattern considered, route duration of routes formed by N intermediate nodes can be computed as the minimum route duration of N 3-node routes. Theoretical analyses and simulations were developed to validate this study. In general, simulation results were very close to the results obtained by the proposed model with an acceptable margin of error. Results from this work can be used to compute the overhead signaling of unicast and multicast routing protocols for mobile ad-hoc networks because every time a route fails, the routing protocol needs to either repair the route locally or find a new route. This route duration model can be used to scale the maximum network size up/down so as to meet minimum route duration requirements in order to ensure a satisfactory communication. In future work, we plan to study the behavior of the proposed model with different mobility models, variable speeds and other heterogeneous conditions. Additionally, we could investigate the relationship between route duration and system performance (throughput and overhead), since this has not been established yet.

Acknowledgments This work is supported in part by research funds from CONACyT grant 47197-Y and PAPIIT grant IN104907-3. *Supported by a UNAM/DGEP scholarship.

References

1. Arbindi, S., Namuduri, K., & Pendse, R. (2005). Statistical estimation of route expiry times in on-demand ad-hoc routing protocols. In *Proceedings of the second IEEE international conference on mobile ad-hoc and sensor systems (MASS 05)*, Washington (USA), November 2005.
2. Bai, F., Sadagopan, N., & Helmy, A. (2003). The IMPORTANT framework for analyzing the impact of mobility on performance of routing protocols for ad-hoc networks. *Ad-Hoc Networks Journal—Elsevier Science, 1*(4), 383–403.
3. Bai, F., Sadagopan, N., Krishnamachari, B., & Helmy, A. (2004). Modelling path duration distributions in MANETs and their impact on reactive routing protocols. *IEEE Journal on Selected Areas in Communications, 22*(7), 1357–1373.
4. Bettstetter, C., Resta, G., & Santi, P. (2003). The node distribution of the random WayPoint mobility model for wireless ad-hoc networks. *IEEE Transactions on Mobile Computing, 2*(3), 257–269.
5. Campbell, A. Eisenman, S., et al. (2006). MetroSense project people-centric sensing at scale. In *Workshop on World-Sensor-Web (WSW 2006)*, Boulder, October 2006.
6. Cho, S., & Hayes, J. (2005). Impact of mobility on connection stability in ad-hoc networks. In *Proceedings of IEEE Communication Society, WCNC 2005* (Vol. 3, pp. 1650–1656), New Orleans, USA.
7. Dijkstra, E. W. (1959). A note on two problems in connection with graphs. *Numerische Mathematik, 1*, 269–271.
8. Fall, K., & Varadhan, K. (2003). The NS manual. The VINT project, UC Berkeley, LBL, USC/ISI and Xerox PARC, July 2003.
9. Gomez, J., & Campbell, A. T. (2007). Using variable-range transmission power control in wireless ad-hoc networks. *IEEE Transactions on Mobile Computing, 6*(1).
10. Gruber, I., & Li, H. (2002). Link expiration times in mobile ad-hoc networks. In *Proceedings of the workshop on Wireless Local Networks (WLN), in IEEE Local Computer Networks Conference (LCN)*, Tampa, Florida, November 2002.
11. Han, Y., La, R., Makowski, A., & Lee, S. (2004). Distribution of path durations in mobile ad-hoc networks—Palm's Theorem at work. In *16th ITC specialist seminar on performance evaluation of wireless and mobile systems*, Antwerp, Belgium, August–September 2004.
12. Hong, X., Gerla, M., Pei, G., & Chiang, C.-C. (1999). A group mobility model for ad-hoc wireless networks. In *Proceedings of ACM/IEEE MSWiM-99*, Seattle, WA, August 1999.
13. Johansson, P., Larsson, T., Hedman, N., Mielczarek, B., & Degermark, M. (1999). Scenario-based performance analysis of routing protocols for mobile ad-hoc networks. In *International*

Conference on Mobile Computing and Networking (MobiCom'99) (pp. 195–206).
14. Leithold, L. (2002). *The calculus 7*. Oxford University: Oxford University Press.
15. Nasipuri, A., Castaneda, R., & Das, S. R. (2001). Performance of multipath routing for on-demand protocols in ad-hoc networks. *ACM/Kluwer Mobile Networks and Applications (MONET) Journal, 6*(4), 339–349.
16. Samar P., & Wicker, S. (2006). Link dynamics and protocol design in a multihop mobile environment. *IEEE Transactions on Mobile Computing, 5*(9), 1156–1172.
17. Triviño, A., Garcia, J., Casilari, E., & Gonzalez, F. J. (2008). Application of path duration study in multihop ad hoc networks. *Telecommunications Systems, 38*, 3–9.
18. Tseng, Y., Li, Y., & Chang, Y. (2003). On route lifetime in multihop mobile ad-hoc networks. *IEEE Transactions on Mobile Computing, 2*(4), 366–376.
19. Turgut, D., Das, S., & Chatterjee, M. (2001). Longevity of routes in mobile ad-hoc networks. In *Proceedings of IEEE Vehicular Technology Conference VTC 2001* (Vol. 4, pp. 2833–2837), Rhodes, Greece
20. Wu, X., Sadjadpour, H. R., & Garcia-Luna-Aceves, J. (2007). Link lifetime as a function of node mobility in MANETs with restricted mobility: Modeling and applications. In *Modeling and optimization in mobile, ad hoc and wireless networks and workshops, 2007. 5th international symposium on WiOpt 2007* (pp. 1–10), April 2007.
21. Yu, D., Li, H., & Gruber, I. (2003). Path availability in ad-hoc networks. *Telecommunications, ICT 10th International Conference, 1*, 383–387.

Author Biographies

Michael Pascoe-Chalke received his B.Sc. in Mechanical-Electrical Engineering in 1997 and the M.Sc. with honors in Electrical Engineering in 2005, both from the National Autonomous University of Mexico (UNAM). Currently he is pursuing Ph.D. studies in Electrical Engineering from UNAM. His areas of interest include location systems and modeling of node mobility in wireless ad-hoc networks.

Javier Gomez received the B.S. degree with honors in Electrical Engineering in 1993 from the National Autonomous University of Mexico (UNAM) and the M.S. and Ph.D. degrees in Electrical Engineering in 1996 and 2002, respectively, from Columbia University and its COMET Group. During his Ph.D. studies at Columbia University, he collaborated and worked on several occasions at the IBM T.J. Watson Research Center, Hawthorne, New York. His research interests cover routing, QoS, and MAC design for wireless ad hoc, sensor, and mesh networks. Since 2002, he has been an Assistant Professor with the National Autonomous University of Mexico. Javier Gomez is member of the SNI (level I) since 2004.

Victor Rangel obtained his Bachelor Degree in Computer Engineering from the National Autonomous University of Mexico (UNAM). He obtained his Master Degree in Data Communication Systems and his doctoral degree in Telecommunications Engineering from the Centre for Mobile Communications Research, The University of Sheffield (England). His Ph.D. thesis focused on the modeling and analysis of Cable TV networks supporting broadband Internet traffic. Dr. Rangel is currently a professor at the Department of Telecommunications Engineering, School of Engineering (UNAM).

Miguel Lopez-Guerrero received his B.Sc. with honors in Mechanical-Electrical Engineering in 1995 and the M.Sc. with honors in Electrical Engineering in 1998, both from the National Autonomous University of Mexico. He received his Ph.D. in Electrical Engineering from the University of Ottawa in 2004. Currently, he is an Associate Professor with the Metropolitan Autonomous University (Mexico City). His areas of interest are in medium access control, traffic control, and traffic modeling.